REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*

2. REPORT TYPE
Technical Papers

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
4847

5e. TASK NUMBER
0159

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20021212 108

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	A		Leilani Richardson

19b. TELEPHONE NUMBER *(include area code)*
(661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

3 separate items enclosed

48470159

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FROM: PROI (STINFO) 02 July 2001

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Frank Mead and Bill Larson, "Laser-Powered, Vertical Flight Experiments at the High Energy Laser System Test Facility"

37th AIAA/ASME/SAE/ASEE JPC & E **(Statement A)**
(Salt Lake City, UT, 08-11 Jul 2001) (Deadline: 06 July 2001)

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PHILIP A. KESSEL Date
Technical Advisor
Space and Missile Propulsion Division

AIAA 2001-3661
Laser-Powered, Vertical Flight Experiments at the High Energy Laser System Test Facility

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36th AIAA/ASME/SAE/ASEE
Joint Propulsion Conference and Exhibit
8-11 July 2001 / Salt Lake City, UT

LASER-POWERED, VERTICAL FLIGHT EXPERIMENTS AT THE HIGH ENERGY LASER SYSTEM TEST FACILITY

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ABSTRACT

In 1996, the Air Force Research Laboratory's Propulsion Division at Edwards AFB initiated the Lightcraft Technology Demonstration (LTD) Program that had as its main objective to launch a laser-propelled vehicle into a suborbital trajectory within a period of 5 years. The concept is a nanosatellite in which the laser propulsion engine and satellite hardware are intimately shared. The forebody aeroshell acts as an external compression surface (i.e., the airbreathing engine inlet). The afterbody has a dual function as a primary receptive optic (parabolic mirror) for the laser beam and as an external expansion surface. The primary thrust structure is the centrally located annular shroud. The shroud provides air through inlets and acts as an energy absorption chamber for plasma formation in the airbreathing mode. In the rocket mode, the air inlets are closed, and the afterbody and shroud combine to form the rocket thrust chamber and plug nozzle. The full-scale vehicle has a focal diameter of one meter and a dry mass of about 1 kg. Fully fueled, this vehicle would have an initial mass of about 2 kg (i.e., a mass fraction of 0.5), and would be launched into orbit with a megawatt-class infrared ground-based laser (GBL). Using a combined-cycle pulsed detonation engine, it would be a single-stage-to-orbit vehicle (i.e., airbreathing with infinite I_{sp} to M=5 and 30 km; a laser thermal rocket with its own on-board propellant at higher altitudes and in space). Once in space, the Lightcraft will use its one-meter diameter optical system to provide, for example, Earth surveys with from 8 to 15 cm resolution in the visible light frequencies from low Earth orbit (LEO). Such a device is simple, reliable, safe, and environmentally clean, and could have a very high all azimuth, on demand launch rate. The current launch model under consideration would launch up to 1,000 vehicles per year. Production costs of about $3,000 for the spacecraft appear reasonable at present.

INTRODUCTION

In a 1969 invention disclosure[6] Mr. Robert Geisler was the first to recognize that laser-propelled rocket were possible with high-powered lasers. He envisioned laser energy transferred via a heat exchanger to a working fluid or used directly to heat fluidized particles dispersed in a working fluid. The working fluid, such as hydrogen or ammonia was to be used to produce thrust with a nozzle as in a conventional rocket. An analysis of this laser propulsion concept was presented in the 1972 Air Force Project Outgrowth Report.[7]

In May of 1972, a seminal article by Dr. Arthur Kantrowitz,[8] of AVCO Everett Research Laboratory, introduced the concept of launching payloads to orbit using high power ground-based lasers. He envisioned using gigawatt class lasers to ablate a solid propellant carried on-board. In a June

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1973 proposal to the Air Force.[7] AVCO described the first toroidal shaped combustion chamber with the throat and expansion cone forming a plug or annular nozzle. Illustrated in Figure 1, this concept had many of the elements of a general class of vehicle concepts that have evolved into the concept called Lightcraft. During the late 1980's, the Lightcraft Technology Demonstrator (LTD) concept was analytically developed at Rensselaer Polytechnic Institute.[1] This study has formed the basis for the current development of the Laser Lightcraft concept.

In 1996, the Air Force Research Laboratory's Propulsion Division at Edwards AFB initiated a program that had as its main objective to launch a Lightcraft into a suborbital trajectory within a period of five years.[1, 2, 5] The full scale vehicle was have a focal diameter of one meter and a dry mass of 1 kg. Fully fueled, this vehicle would have an initial mass of about 2 kg (i.e., a mass fraction of 0.5), and would be launched with a megawatt-class infrared ground-based laser. It would be a single-stage-to-orbit vehicle (i.e. airbreathing to M=5 and 30 km (infinite I_{sp}); a laser thermal rocket with its own on-board propellant at higher altitudes and in space) as in a combined-cycle pulsed detonation engine. Once in space, the Lightcraft would use its one-meter diameter optical system, with from 8 to 15 cm resolution in the visible light frequencies, to provide Earth surveys. Such a device is simple, reliable, safe, and environmentally clean, and could have a very high all azimuth, on demand launch rate. The current launch model under consideration would launch up to 1,000 vehicles per year for under $500 of electrical power.

The Lightcraft Technology Demonstration Program was planned in five phases. Phase I, Lightcraft Concept Demonstration, was to demonstrate the feasibility of the basic concept. This phase ended in December 1998. Phase II, Lightcraft Vertical Launches to Extreme Altitudes, is currently a five-year effort designed to extend Lightcraft flights to 30 km in sounding rocket trajectories with a 100 kW CO_2 laser. Phase III, Lightcraft Dual Mode Vehicle, is a two-year effort designed to launch the first laser-propelled vehicle, a functional Lightcraft, into a low Earth orbit

Under Phase I, performance was measured with a pendulum impulse and piezoelectric thrust stands, shadowgraph and beam propagation (to 90 m) studies were accomplished, a pointing and tracking system was developed and demonstrated on horizontal wire-guided flights outdoors to 122 m, and outdoor vertical free-flights approaching 30 m were successfully conducted.[5] Low Mach number wind tunnel tests were also accomplished with a 23-cm diameter model, and later reported.[4] The basic conclusion of all this work was that the feasibility and basic physics of the Lightcraft concept had been adequately demonstrated, but that a much larger, 100 kW class, laser would be required to completely accomplish Phase II.

Phase II, initiated in Jan 1998, continued with the performance characterization of several #200 series models, but used the 10 kW laser from Phase I.[3] The #200 series consists of a number of different sized vehicles all scaled to the same optical f-number. These models exhibit stability and self-centering in the near-field laser beam. Outdoor vertical free flights with the Model #200-solid ablative rocket (SAR) impacted the plywood beam dump at about 40 m in Jul 1999.[5]

With the extended lifetime and enhanced performance demonstrated by the addition of an ablative propellant, it was proposed to develop a laser "hand-off" technique using the Model #200-SAR vehicle and the PLVTS laser.[5] This is a complex maneuver, involving several different optical telescopes, that requires practice and development. The goal of the current hand-off experiments, is to achieve altitudes on the order of 150 to 500 m.[5] Testing to these extreme altitudes, without a beam dump, requires NORAD clearance and coordination with WSMR flight and safety groups. Planning for these flights must be coordinated with these agencies six weeks in advance of the flight test date.

CURRENT ACTIVITIES

Theoretical Studies

NASA's Marshall Space Flight Center has developed a CFD model of the Lightcraft using air as a propellant.[9, 10] This model has been used to predict performance over a wide range of conditions, including altitude. At the AFRL, theoretical analysis of the overall energy conversion of an Lightcraft propelled by laser heated air has been presented and is continuing.[11, 12] Based upon the Lightcraft geometry that incorporates an inverted parabolic reflector that focuses laser energy into a torus-shaped volume where it is absorbed by a unit of propellant mass that is subsequently expanded in the geometry of a aerospike-type plug nozzle.

Figure 1 shows a transformation of the chemical equilibrium Mollier diagram for air up to 24,000 °K.[9] Figure 1 is based on the database maintained at NASA's Glenn Research Center[13] which is certified accurate up to 20,000 °K and is based upon extended 9-parameter fits to enthalpy, heat capacity, and entropy of neutral species and singly charged ions. Above 20,000 °K, doubly charged ions begin to contribute but these are not included in the database.

Figure 1 also shows a series of vertical lines which are representations of equilibrium isentropic expansions that originate from initial states located along the constant density line, $\rho = 1.18$ kg/m^3, and specific internal energies ranging from 1 to 100 MJ/kg. Since the entropy of the initial and final states are equal, the thermodynamic state of the propellant in the exit surface is uniquely defined when only one additional property in the exit surface is specified, such as the exit pressure or the expansion ratio, ε, which is the ration of the area of the exit surface to the area of the sonic surface or nozzle throat.

The analysis of experimental results showed that the 10-cm Lightcraft converted ~ 25% of the incident laser energy to propellant kinetic energy: $\alpha \approx 0.25$. The upper limit to alpha was obtained from thermodynamic analysis of the conversion of propellant internal energy to propellant kinetic energy when air at a specified internal energy and density undergoes optimum blowdown expansion to 1 bar ambient pressure. The equation of state of the partially ionized propellant under conditions of chemical equilibrium is captured in the analysis. For laser-heated air at STP density (1.18 kg/m^3), the upper limit alpha varies from 0.33 to 0.30 as the internal energy decreases from 100 to 1 MJ/kg (~24,000 to ~2,000 °K) when chemical equilibrium is maintained during blowdown expansion. For frozen composition expansion using the initial composition, the upper limit of alpha ranges from 0.25 to 0.27 as the internal energy varies from 100 to 1 MJ/kg. For laser heated air at the Mach 5 stagnation density (5.90 kg/m^3) these values increase by ~ 15%.[6,7]

Study of Laser and Vehicle Requirements and Costs

At the beginning of FY2001, a study program was initiated with Flight Unlimited in Flagstaff, AZ, to determine if Lightcraft vehicles powered by energy beamed from ground-based or airborne lasers can cost effectively perform future crucial Air Force missions, and to provide parametric models for exploring the potential of Lightcraft and laser systems for the estimated range of laser propulsion efficiencies that appear achievable.[11] This study is to be built on the extensive Lightcraft laser propulsion technology that has already been developed by theoretical and experimental work of the Air Force Research Laboratory and others. The study is divided into five tasks. Task 1 is titled "Lightcraft Mission Selection" in which the contractor will select candidate missions for Air Force applications and parameterize the mission requirements in terms of payload, weights, and sizes versus kinematic performance. Task 2 is titled "Lightcraft Parametric Model Development" in which a simple parametric model of the Lightcraft is developed that predicts characteristics (thrust, drag, weight, and cost) as a function of input beam parameters (wavelength, power, diameter, etc.), altitude, range from the laser, Mach number, inlet performance, and other appropriate efficiency factors. Task 3 titled "Ground Based Laser Model Development" will develop a parametric model of the ground-based laser system performance and cost. Task 4 titled "Vehicles synthesis and system Cost Estimation" will apply the models developed in Tasks 2 and 3 to the mission(s) selected in Task 1 to determine the baseline laser propelled vehicle configurations and costs. Task 5 is cost optimization and preparation of a final report with an oral presentation of the study's results.

German Collaboration

At the end of 1998, the Institute of Technical Physics of the German Aerospace Center began some basic investigations of a simple lightcraft configuration, and wire-guided flights and pendulum measurements of the impulse coupling coefficients were conducted in the laboratory. The lightcraft was made of a thin Aluminum sheet drawn over a paraboloid, and had a diameter of 10 cm and a height of 62.5 cm. The focal distance from the apex is 1 cm. The inner was polished for better reflectance. The mass of the shell without any modification was 17 g and was increased by 5g when a thin tube was added for sliding on a wire. Tests of the lightcraft utilized the DLR multi-spectral laser, operating with CO_2 gas at a wavelength of 10.6 microns. Performance results of the lightcraft were presented at Santa Fe, NM in 2000.[15]

In Sep 2000, the AFRL initiated an experimental program through the European Office of Aerospace Research and Development (EOARD) with the Institute of Technical Physics, Stuttgart, Germany. Due to the differences in the experimental setup and the reported coupling coefficients, it was in our common interest to directly compare the performance. Arrangements were made to demonstrate the AFRL experimental procedures and pendulum impulse test stand with the Lightcraft for the Germans at HELSTF. This was done in Oct 2000. The same experimental equipment (including the Lightcraft) that had been used for the demonstration was then packaged and sent to Stuttgart with the data so that the Germans could duplicate the HELSTF tests and note any differences that might be attributable to their laser. This was done, and a series of experiments coupling coefficient was measured in both air and with Delrin ablative

propellant when the laser with both stable and unstable resonator modes. With the beam from the stable resonator, achievable pulse energies were limited to about 310 J due to physical size limits. The unstable resonator allowed pulse energies up to 410 J. All tests were conducted in ambient air.[16]

The results showed that the two pendulums did not give the same results. This could be accounted for through dynamic and structural analysis. It is believed that the geometrical factors with respect to the prevailing, mass dependent physical pendulum length are the source for an error in the measurement with the AFRL pendulum. The variation in performance of the AFRL Lightcraft varied less than 6%, independent of resonator type and operation with or without Delrin. In contrast, the variations of the German lightcraft performance were in excess 10%. The data obtained with the stable resonator in the tight focus mode most closely agrees with the published Lightcraft performance. Improved performance was obtained with the unstable resonator.[16]

Several other striking differences were noted. The AFRL Lightcraft with its toroidal shape showed different and stronger dependencies on the pulse energy compared to the German lightcraft with its parabolic shape. The performance of the AFRL Lightcraft with air as the propellant was poor when compared to the German lightcraft. With Delrin in the AFRL Lightcraft, the two concepts performed comparably at moderate pulse energies, but at sufficiently high pulse energies the AFRL Lightcraft clearly outperformed the German lightcraft.[16]

Testing at White Sands Missile Range

The objective of the current Phase II vertical flight test program is to extend Lightcraft vertical free flights to significantly higher altitudes. Using the available 10 kW, PLVTS, CO_2 electric discharge laser[5] at the HELSTF, White Sands Missile Range (WSMR), New Mexico, the vertical flight test program is attempting vertical free-flights to altitudes in the range of 150 to 500 m with the 1/10th-scale model (200-3/4th SAR) Lightcraft. Figure 2 illustrates with an artist's conception the model that is used for testing. This figure shows the laser light from the lower left impinging on the parabolic surface and being focused in a circular ring on the inside of the shroud where the intensity is sufficient to form a high temperature, high pressure plasma which expands out the back to provide thrust for each pulse of the laser. As illustrated, the inside of the vehicle is hollow. The total weight is about 30 g.

For these flights, the laser is usually operated at 25 pulses per second with 18 μs pulse widths.[5] Three different telescopes are used for these flights. The first telescope, the "launch telescope" used for lift-off, is the same telescope that's been used for flight-testing during past flight experiments. The second telescope is a "transition telescope" used to bridge the distance between the effective operational altitudes (distances) of the launch telescope and the 50-cm Field Test Telescope (FTT).[5] In other words, there is an intermediate distance in which neither the launch telescope nor the FTT works well with the Lightcraft.

Flight test durations much over three seconds have in the past resulted in the destruction of the Aluminum shroud. One of the beneficial effects of the Delrin propellant has been to extend the flight time, and thus altitude, because of the cooling effects of the ablation process. But this has always been considered as only an interim approach until high temperature materials can be incorporated into the vehicle construction.

The first 1/10th-scale model composite, ceramic shroud has been fabricated (see Fig. 3) and tested in the laboratory on the pendulum impulse test stand. This new shroud is comprised of an amorphous SiNC matrix reinforced with a Nicalon fiber. It was fabricated by Composite Optics Inc., San Diego, CA.

Figure 4 illustrates a comparison of performance obtained on the pendulum impulse test stand.[5] The well-established performance of the Aluminum shroud is illustrated by the bottom curve in Figure 4. The upper curve illustrates the performance of the Nicalon shroud, which was tested starting at the lowest energy per pulse level, and proceeding; step wise, to the higher energy per pulse levels. This was done because we wanted to establish the upper limit at which this new shroud would survive. As can be seen in Figure 4, the shroud survived to over 400 J. At that point, some separation of the fiber "butt" joint was seen, and the experiments were stopped. The performance at the lower energy levels appears to be high because of initial outgassing. At the higher energy levels, the Aluminum and Nicalon performance appears to be essentially the same. We suspect that if an additional set of tests were conducted after outgassing had been eliminated, the lower energy levels would essentially match the Aluminum curve. This will be investigated in the future.

Laser Beam Propagation Studies

The Air Force Research Laboratory's Propulsion Directorate examined the use of high power CO_2 lasers focused at long ranges through the atmosphere for purposes of high specific impulse

propulsion of small payloads into the upper atmosphere and into space. Defense Strategies & Systems Inc. of Great Falls, VA, performed an analysis of propagation of such lasers under varying atmospheric conditions using scenarios of interest for this application.[17]

They examined the performance that could be achieved by pointing and focusing a high power CO_2 laser, operating at an isotopic line near 11.2 microns, into small spot sizes under the range of conditions likely to control achievable intensities. Figure 5 illustrates the parameter selection for this study. Off-zenith angles down to 19° above the horizon were examined for three different variation of atmosphere. Typical weather conditions at WSMR were considered as representative of possible launch conditions. In the study, Condition 1 denotes the best conditions to be experienced routinely; Condition 2 denotes average conditions; and, Condition 3 is for degraded conditions that may be experienced 10% of the time. These atmospheric variations differed mainly in the amounts of aerosols present at high altitudes. This analysis included the combined effects of thermal blooming, turbulence, and linear extinction. Thermal blooming is much less of a problem than it would be for the more common version of CO_2 lasers at 10.6 microns. The study also included the effects of laser beam quality, transmitter optics quality, and pointing jitter of the transmitted beam. Figure 6 illustrates the propagation of isotopic CO_2 through the atmosphere under Condition 3. As a reference, the 10-cm Lightcraft reaches an irradiance of 10^7 W/cm^2 at a pulse energy of about 608 J.

The study determined that, under most meteorological conditions, a 3 MW isotopic CO_2 laser coupled with a 3-meter diameter, ground-based beam director can propagate a beam with more than 140 W/cm^2 to a distance greater than 30 km into the atmosphere without the need for an adaptive optics system. That flux density was taken as the minimum for effective Lightcraft propulsion. They assumed meteorological conditions likely to bracket those that will be experienced at the White Sands Missile Range (WSMR), NM. Detailed data describing those expected conditions were collected and provided in the report.[14]

Using those values and a detailed propagation model they had developed, Defense Strategies & System Inc calculated the expected irradiance and far field beam diameters as a function of transmitted power, range, beam director diameter and zenith angle, with and without adaptive optics.

The zero degree zenith angle has the highest irradiance for a given laser power. At larger zenith angles measured from the vertical, the beam spends more time in the lower atmosphere, suffers more due to thermal blooming and turbulence, and reaches a peak irradiance at lower transmitted laser powers.

The best conditions for Lightcraft propagation will most likely occur during the winter months and during early morning or early evening, when the adiabatic lapse rate changes sign and the turbulence reaches a minimum. The least favorable conditions will most likely occur during the summer months in the middle of the day. But, like weather, both extremes will occur at many other times and seasons.

The study indicates that, even under degraded meteorological conditions, half the transmitted laser energy can be maintained within a 1-meter Lightcraft receiving aperture beyond 30 km for a zenith angle of 0° and beyond 28 km for a zenith angle of 45°. Beam diameters could be controlled to less than 1 m out to 80 km, although that would probably not be justified for this endoatmospheric application.

Low altitude turbulence is the dominant beam spreading mechanism for which the adaptive optics is compensating. For long-range propagation out to ranges well beyond 100 km, larger optics, higher power levels, and adaptive optics compensation would be desired. In the case of a high-altitude Lightcraft, the beam diameter would be desired to be not much larger than a meter out to ranges of several hundred kilometers. If a turning mirror or relay mirror were to be used, that mirror would be at 500 km or greater to prevent drag from the upper atmosphere. For this scenario, a beam of less than 10 m would be desired at ranges out to 1,000 km.

Lateral and Attitude Control Propulsion

In May 2000, the AFRL initiated a Phase I Small Business Innovation Research (SBIR) contract with SY Technology, Inc., in Huntsville, AL, to start the development of a lateral and attitude control system for the Lightcraft. Lateral control is required to keep the vehicle properly positioned in the laser beam throughout its launch into orbit. Attitude control is required to keep the vehicle oriented properly with respect to the beam (i.e., pointed at the GBL). The Phase I goal is to determine the requirements of the control system and then to design and demonstrate control technologies which meet these requirements.[18] The Phase I control concept is based upon the dimensions of a quarter-scale (25 cm) Lightcraft design, and has not yet been completed. If a Phase II SBIR program is initiated in the future, both laboratory and flight tests of a quarter-scale Lightcraft will be required to fully develop the lateral and attitude control system.

Development of a 25-cm (¼th-Scale) Vehicle

The 10-cm Lightcraft design has been scaled to a quarter-scale (25-cm) focal diameter size. Fabrication drawings for Aluminum have been completed. Plans are being formulated to develop a completely composite vehicle at this size. The basic work necessary for a composite (Nicalon) shroud has been successfully completed at the 1/10th-scale size. What remains is to develop an afterbody (parabolic mirror) and forebody that can handle the heat loads that are predicted during flights into space. This development of an all-composite Lightcraft would go "hand-in-hand" with that of the control system development, with the goal of developing and eventually testing a fully controlled composite Lightcraft. This could be accomplished within the next two years.

One of the key developments to the success of the dual mode propulsion concept upon which the Lightcraft is based is the use of air as a propellant during operation within the atmosphere. This requires the development of air inlets that can give some assistance at subsonic speeds and become fully functional at supersonic speeds. Special attention must be paid to this development when considering the transonic regime where losses can become excessive. To this end, the program has hired an aerodynamicist, Frank Herr, who retired from the Marquardt ramjet program several years ago. Frank is working closely with Air Force engineers and designers to develop functional air inlets for the quarter-scale vehicle. Preliminary designs have been prepared and are now being evaluated.

Progress Toward a 100-kW Class Laser

Last fall, NASA's Marshall Space Flight Center and the AFRL jointly funded the transfer of the "CORA" laser from MIT's Lincoln Laboratory to the HELSTF. This Government laser had been placed on the surplus list, and would have been sold as scrap if not claimed by some agency. This 10 kW CO_2 laser produces a beam that is very close to the diffraction limit. As such, it has been tentatively planned to mate this laser with the PLVTS laser in master oscillator/power amplifier (MOPA) arrangement. In this configuration, a 100 kW laser beam output could be obtained. This could be used for flight testing of quarter- and half-scale vehicles to very high altitudes and supersonic speeds in the not too distant future. The cost estimate to put this 100 kW system together is about $2M. Additional funds will be required to construct an appropriate optical system for the extreme distances that the beam will be propagated. The optical system size and cost have already been predicted from previous studies.

REFERENCES

1. Myrabo, L.N., Messitt, D.G., & Mead, F.B., Jr., "Ground and Flight Tests of a Laser Propelled Vehicle," AIAA 98-1001, 36th Aerospace Sciences Meeting & Exhibit, Reno, NV, 12-15 Jan 1998.

2. Mead, F.B., Jr., Myrabo, L.N., & Messitt, D.G., "Flight and Ground Tests of a Laser-Boosted Vehicle," AIAA 98-3735, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conf., Cleveland, OH, 13-15 Jul 1998.

3. Messitt, D.G., Myrabo, L.N., Mead, F.B., Jr., "Laser Initiated Blast Wave for Launch Vehicle Propulsion," AIAA 2000-3848, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conf., Huntsville, AL, 17-19 Jul 2000. 6 ✓ 0

4. Panetta, A.D., Negamatsu, H.T., Myrabo, L.N., Minucci, M.A.S., Mead, F.B., Jr., "Low Speed Wind Tunnel Testing of a Laser Propelled Vehicle," SAE International and AIAA 1999-01-5577, 1999 World Aviation Conf., San Francisco, CA, 19-21 Oct 1999.

5. Mead, F.B., Jr., Squires, S., Beairsto, C., & Thurston, M., "Flights of a Laser-Powered Lightcraft During Laser Beam Hand-off Experiments," AIAA 2000-3484, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conf., Huntsville, AL, 16-19 Jul 2000.

6. Geisler, R.L., "Laser Augmented Rocket Propulsion and Auxiliary Power," Air Force Invention No. 6157, Invention Disclosure, May 1969. ?

7. "Advanced Propulsion Concepts – Project Outgrowth," AFRPL-TR-72-31, F.B. Mead, Jr., Ed., Air Force Rocket Propulsion Laboratory, Edwards AFB, CA, Jun 1972. – TR in Distrib'n A – OK.

8. Kantrowitz, A., "Propulsion to Orbit by Ground-Based Lasers," Astronautics & Aeronautics, Vol. 10, No. 5, May 1972, pp. 74-76.

9. Wang, T.-S. et al., "Performance Modeling of an Experimental Laser Propelled Lightcraft," AIAA 2000-2347, 31st AIAA Plasmadynamics and Lasers Conference, Denver, CO, 19-22 June 2000.

10. Wang, T.-S., Chen, Y.-S., and Liu, J., "Effect of Pulse Width on Laser Lightcraft Performance," AIAA

2000-3664, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Salt Lake City, UT, 8-11 July 2001

11. Larson, C.W. & Mead, F.B., Jr., "The Rocket Equation, Coupling Coefficients, Mollier Diagrams, and Optimization of Laser Propulsion, or Energy Conversion in Laser Propulsion," AIAA 2001-0646, 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, 8-11 Jan 2001

12. Larson, W.C., Mead, F.B., Jr., & Kalliomaa, W.M., "Energy Conversion in Laser Rocket Propulsion," To be submitted in the AIAA J. of Propulsion & Power, 2001.

13. McBride, B.J. and Gordon S., "Computer program for Calculation of Complex chemical Equilibrium Compositions and applications, II. Users Manual and Program Description," NASA Reference Publication 1311, Lewis Research Center, Cleveland, OH, Jun 1996.

14. Froning, H.D., "Proposed Study to Determine the Effectiveness and Cost of a Laser-Propelled "Lightcraft" Vehicle System," Proposal to the AFRL/PRS, Edwards AFB, CA, 31 Aug 2000. ?

15. Schall, W.O., et al., "Lightcraft Experiments in Germany," Proceedings of SPIE, High-Power Laser Ablation III, V. 4065, Claude R. Phipps ed., 24-28 Apr 2000.

16. Schall, W.O. et al., "U.S. German Lightcraft Impulse Measurements," Final Report. EOARD Contract No. F61775-00-WE033, Apr 2001. ?

17. Pike, H.A. and Bold, M.M., "Laser Propagation for Lightcraft LEO/GEO Scenarios," Final Report for the Air Force Research Laboratory, Edwards AFB, CA, Aug 2000. ?

18. "Attitude Control System for Laser Lightcraft," Phase I Small Business Innovation Research (SBIR) Program Proposal, Proposal No. F001-0666, Topic No. AF00-221, 7 Jan 2000. ?

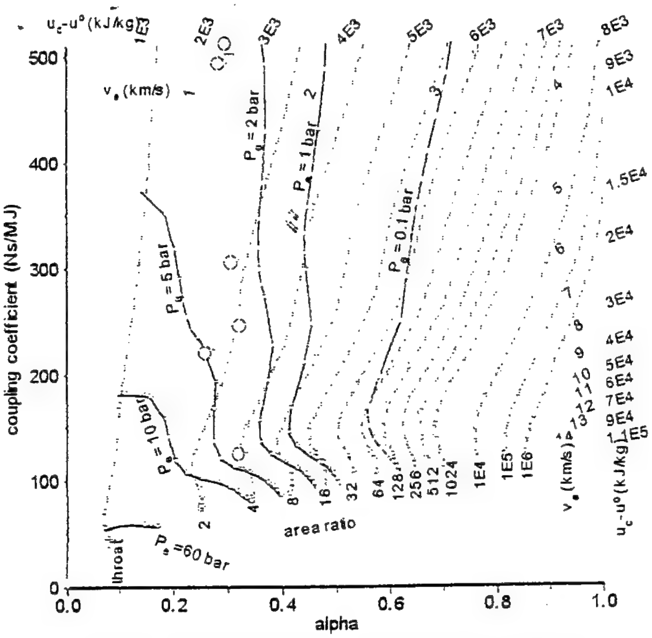

Figure 1. Thermodynamic Characteristics of Air

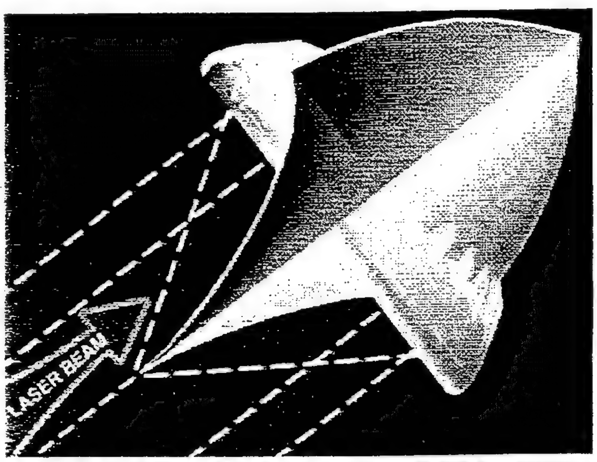

Figure 2. Artist's Cutaway Lightcraft Drawing

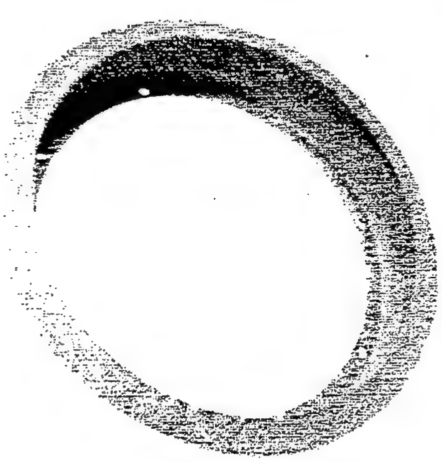

Figure 3. COI Nicalon Shroud

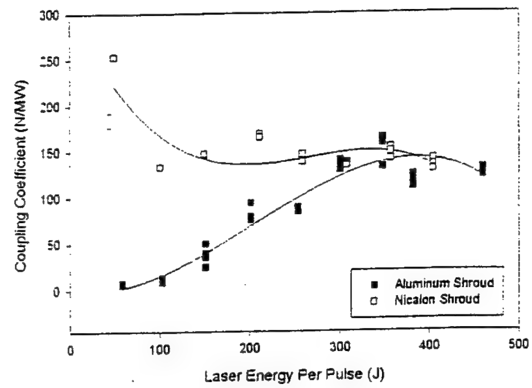

Figure 4. Comparison of Nicalon and Aluminum Shroud Performance

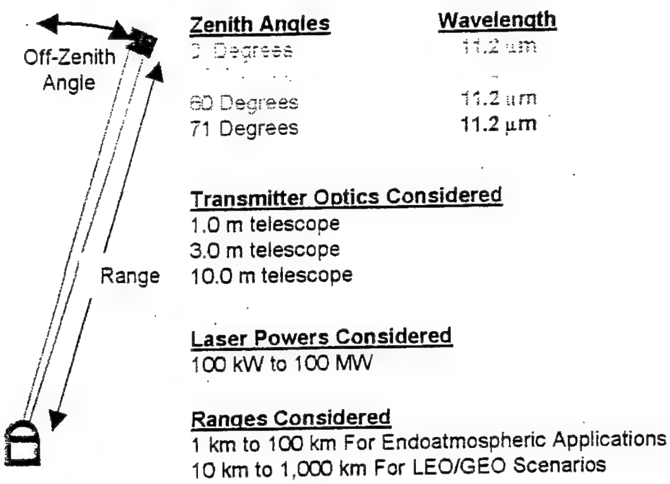

Figure 5. Lightcraft Scenario Parameters

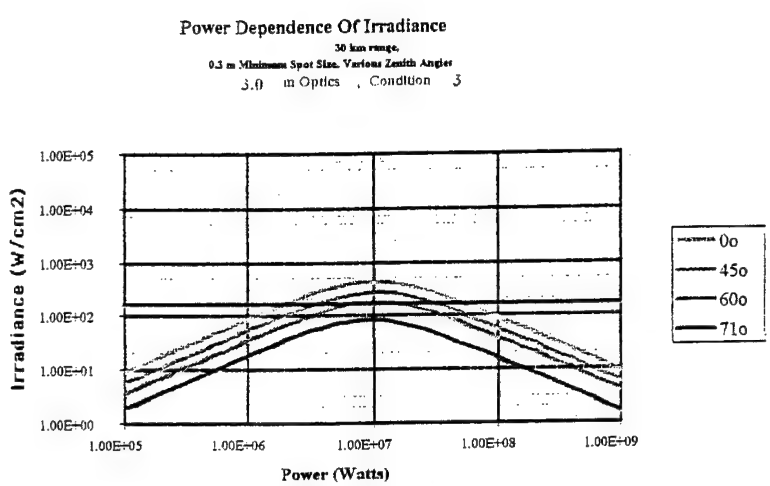

Figure 6. Power Dependence of Irradiance

AIAA 2001-3661

Laser-Powered, Vertical Flight Experiments at the High Energy Laser System Test Facility

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36th AIAA/ASME/SAE/ASEE
Joint Propulsion Conference and Exhibit
8-11 July 2001 / Salt Lake City, UT

Overall Energy Conversion in Laser Propulsion Mission

$$E_f = \tfrac{1}{2} m_f v_f^2 = \eta\alpha\beta\gamma E_L$$

η = propulsion efficiency (jet kinetic energy to vehicle kinetic energy)

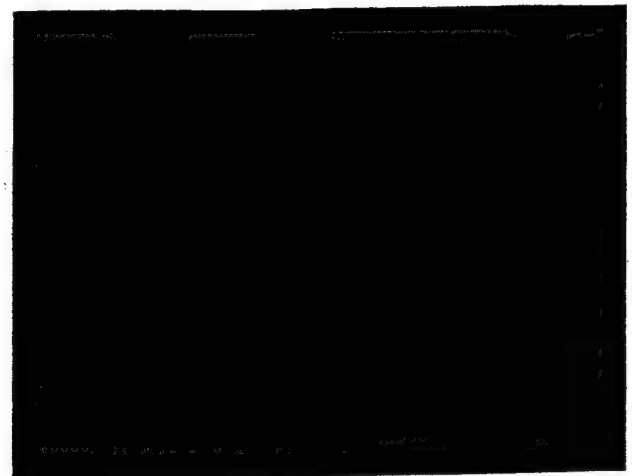
α = expansion efficiency (internal propellant energy to jet kinetic energy)

β = absorption efficiency (laser energy at vehicle to internal propellant energy)

γ = transmission efficiency (laser energy at ground to laser energy at vehicle)

Pulsed Laser Vulnerability Test System (PLVTS)

- Original Performance
  - 800 joules/pulse
  - 10 Hz
  - 30μsec pulses
- Modified Performance
  - 1998
    - 400 joules/pulse
    - 28 Hz
    - 18μsec pulses
  - 1999
    - 150 joules/pulse
    - 30 Hz
    - 5μ:sec pulses



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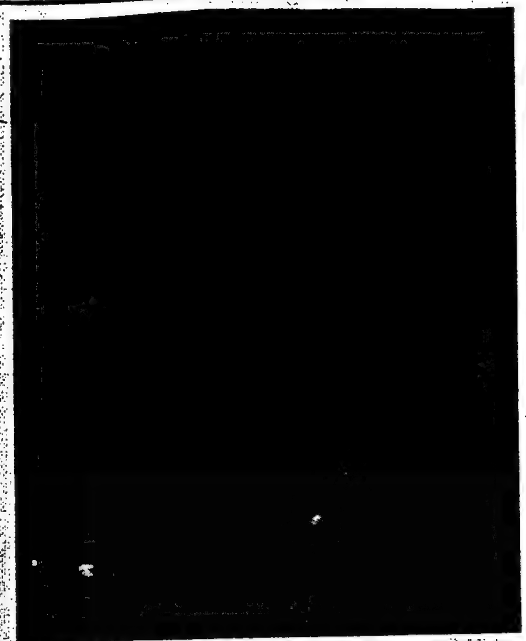
Optical Bench Set Up At 500-Ft Mark

29-Meter Outdoor Vertical Flight



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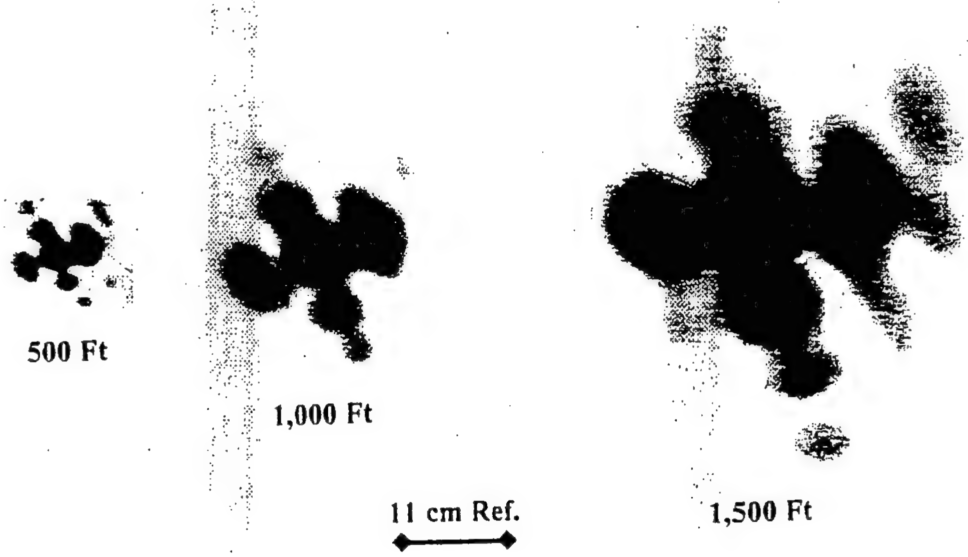
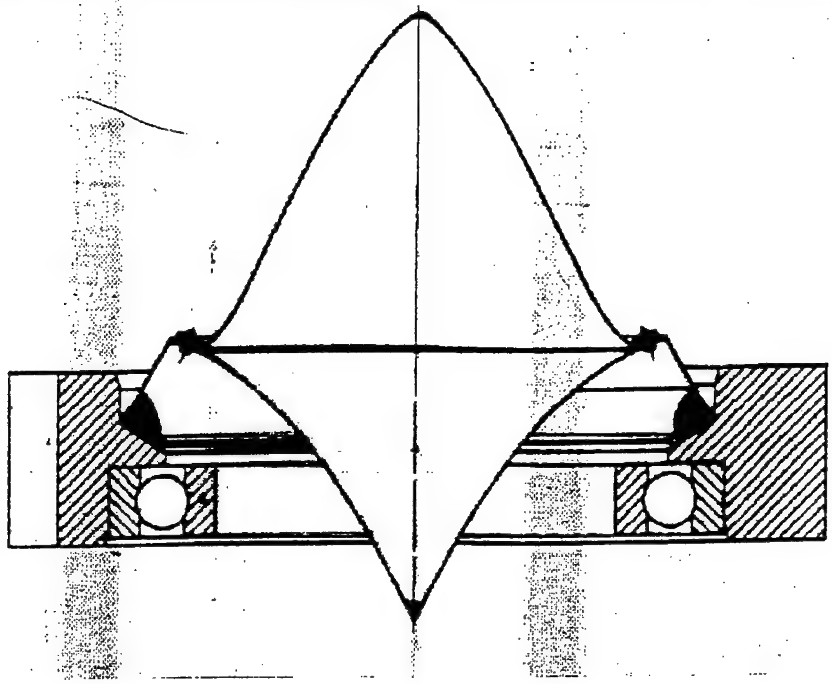
FTT Beam Burn Patterns



Launch Stand Illustration

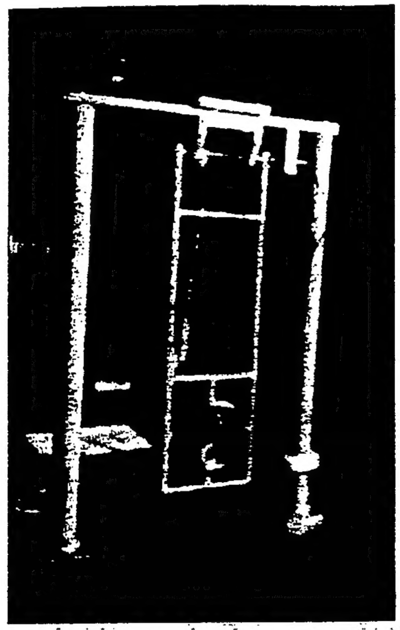


Normalized absorption volume for air at 1.18 kg/m^3 as a function of internal energy and laser energy.

u	V_{abs}/β, normalized absorption volume, cm^3					
MJ/kg	E_L=50 J	E_L=100 J	E_L=150 J	E_L=200 J	E_L=300 J	E_L=400 J
1	42.3	84.7	127.1	169.4	254.2	338.9
2	21.1	42.3	63.5	84.7	127.1	169.4
3	14.1	28.2	42.3	56.5	84.7	112.9
4	10.5	21.1	31.7	42.3	63.5	84.7
5	8.47	16.9	25.4	33.9	50.8	67.8
6	7.06	14.1	21.1	28.2	42.3	56.5
7	6.05	12.1	18.1	24.2	36.3	48.4
8	5.30	10.5	15.8	21.1	31.7	42.3
9	4.71	9.42	14.1	18.8	28.2	37.6
10	4.24	8.47	12.7	16.9	25.4	33.9
15	2.82	5.65	8.47	11.3	16.9	22.6
20	2.12	4.24	6.36	8.47	12.7	16.9
30	1.41	2.82	4.24	5.65	8.47	11.3
40	1.06	2.12	3.18	4.24	6.36	8.47
50	0.85	1.69	2.54	3.39	5.08	6.78
60	0.71	1.41	2.12	2.82	4.24	5.65
70	0.61	1.21	1.82	2.42	3.63	4.84
80	0.53	1.06	1.59	2.12	3.18	4.24
90	0.47	0.94	1.41	1.88	2.82	3.77
100	0.42	0.85	1.27	1.69	2.54	3.39
110	0.39	0.77	1.16	1.54	2.31	3.08

Pendulum Impulse Test Stand

AIAA Short Course 2001



C-LINE #62027
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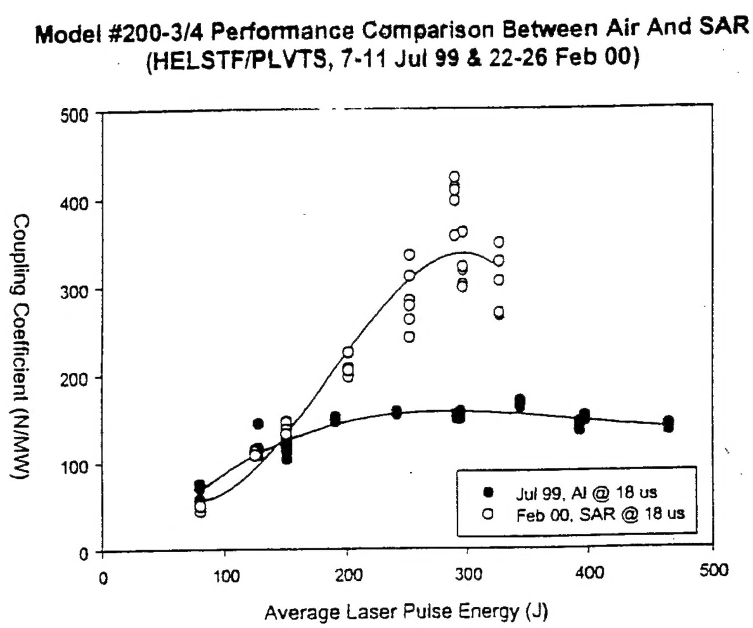
Laser Lightcraft Measured Performance

AIAA Short Course 2001



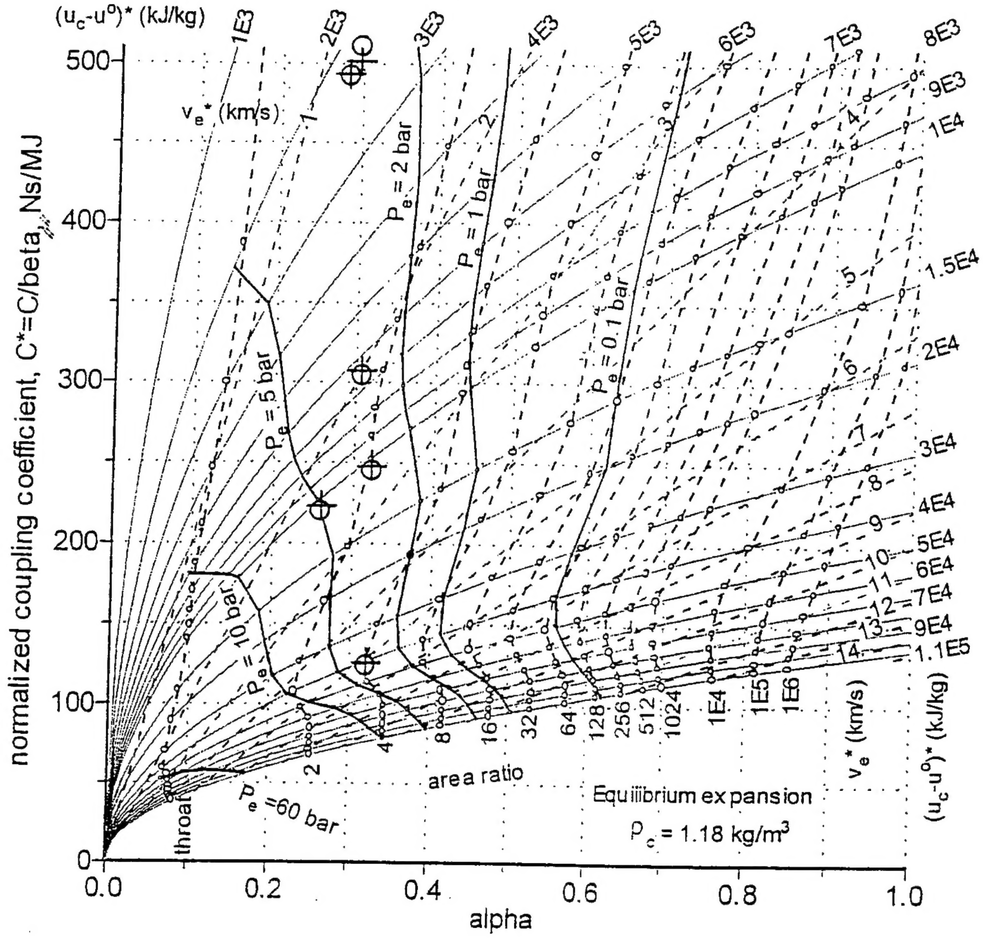
Thermodynamic properties of Mach 5 air at stagnation density,

$\rho = 5.90$ kg/m^3.

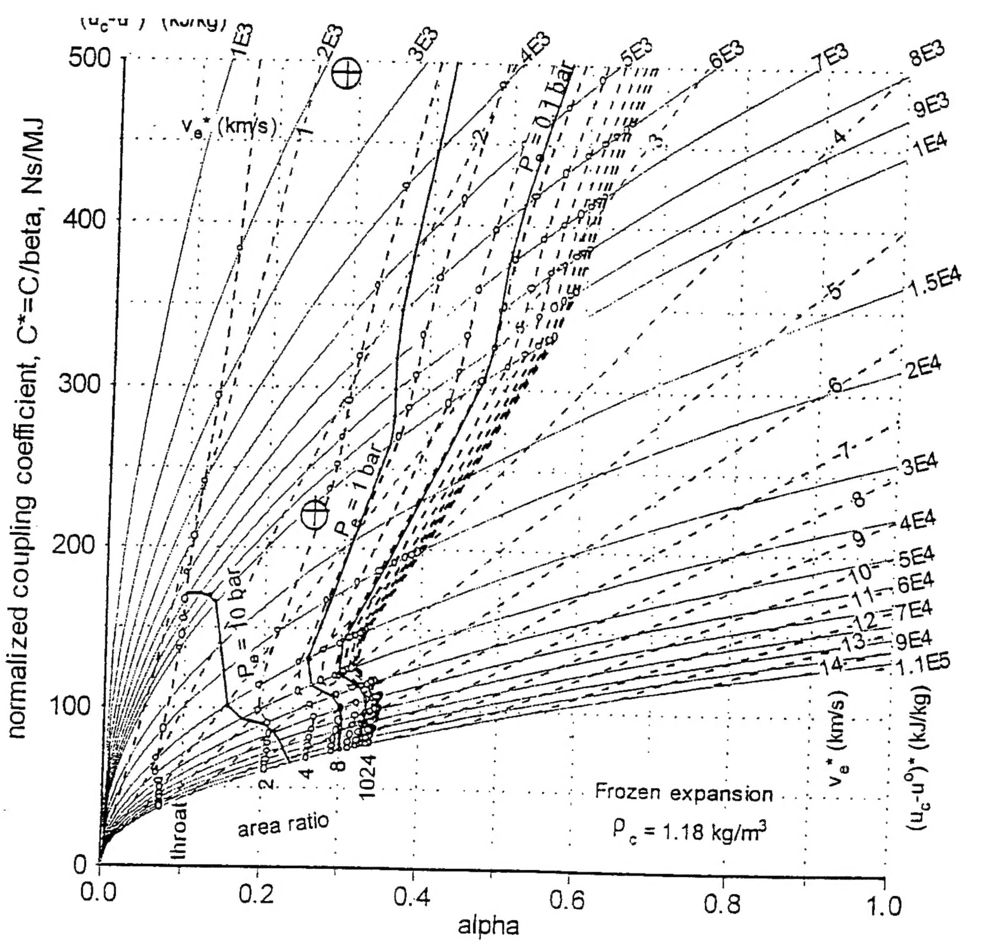
u	T	P	h	s	c_p	M	X(e$^-$)	v_a	c_p/c_v
MJ/kg	10^3 K	bar	MJ/kg	KJ/kg K	KJ/kg K	kg/kmol		km/s	
0.102	0.560	9.492	0.263	6.864	1.042	28.965	0	0.471	1.38
1	1.6	27.1	1.5	7.7	1.25	28.97	4e-13	0.77	1.30
2	2.6	43.2	2.7	8.2	1.45	28.95	6.E-11	0.96	1.25
3	3.3	56.5	4.0	8.6	1.85	28.73	2.E-08	1.08	1.21
4	3.9	67.7	5.1	8.9	2.33	28.19	3.E-07	1.17	1.20
5	4.4	78.2	6.3	9.1	2.65	27.46	2.E-06	1.26	1.20
6	4.8	88.9	7.5	9.3	2.71	26.69	6.E-06	1.35	1.22
7	5.3	100.3	8.7	9.5	2.61	25.96	2.E-05	1.45	1.23
8	5.8	112.4	9.9	9.7	2.55	25.32	4.E-05	1.53	1.23
9	6.3	124.5	11.1	9.9	2.69	24.79	8.E-05	1.61	1.22
10	6.7	135.8	12.3	10.0	3.04	24.32	1.E-04	1.67	1.21
15	8.2	182.0	18.1	10.7	5.49	22.19	6.E-04	1.91	1.18
20	9.2	222.3	23.8	11.2	7.36	20.32	1.E-03	2.11	1.18
30	10.8	304.9	35.2	12.2	8.05	17.41	3.E-03	2.49	1.20
40	12.7	404.9	46.9	13.1	5.52	15.45	1.E-02	2.92	1.24
50	15.6	534.8	59.1	13.8	4.28	14.33	3.E-02	3.39	1.27
60	18.4	667.9	71.3	14.4	5.20	13.54	8.E-02	3.78	1.26
70	20.8	794.6	83.5	14.9	6.32	12.81	1.E-01	4.13	1.27
80	22.8	919.9	95.6	15.4	7.26	12.14	2.E-01	4.45	1.27
90	24.6	1046.6	107.7	15.8	7.99	11.52	2.E-01	4.76	1.28

Thermodynamic properties of equilibrium air,
$\rho = 1.18$ kg/m^3.

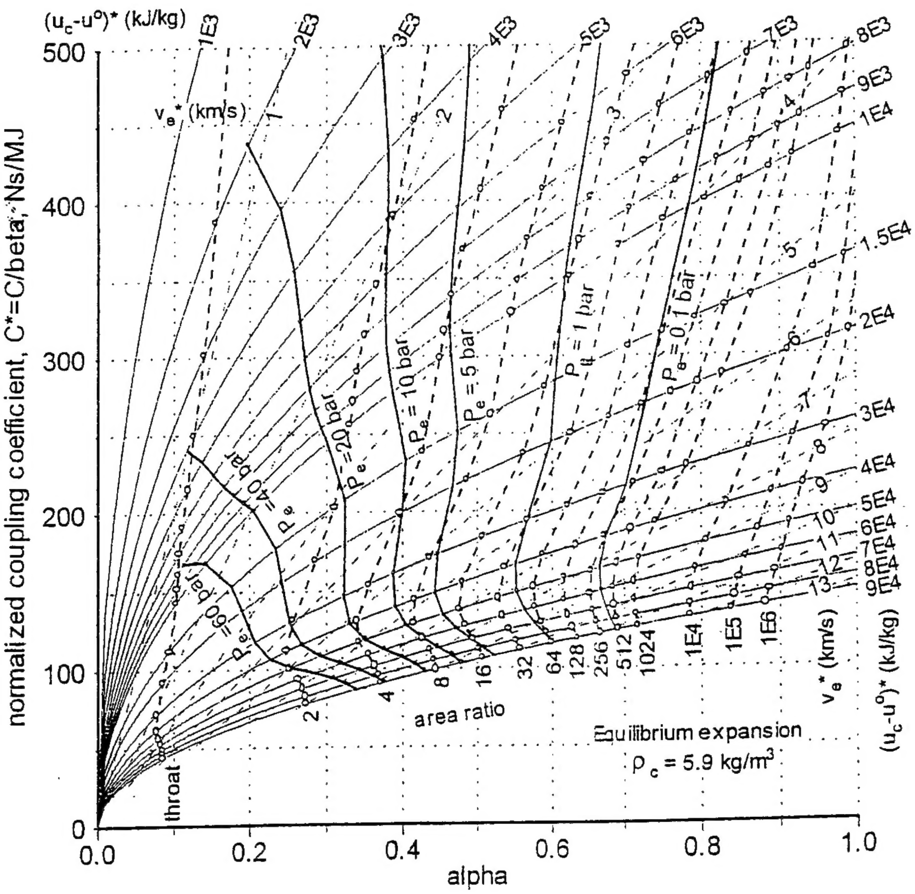
u	T	P	h	s	c_p	M_m	X(e$^-$)	v_a	c_p/c_v
MJ/kg	10^3 K	bar	MJ/kg	KJ/kg K	KJ/kg K	kg/kmol		km/s	
-0.9	0.298	1.00	0	6.864	1.005	28.965	0	0.35	1.40
1	1.6	5.4	1.5	8.2	1.25	29.0	4E-10	0.77	1.30
2	2.5	8.6	2.7	8.7	1.51	28.9	3.E-09	0.95	1.24
3	3.2	11.1	3.9	9.0	2.16	28.6	3.E-08	1.06	1.20
4	3.7	13.1	5.1	9.3	2.83	27.8	3.E-07	1.15	1.19
5	4.1	15.0	6.3	9.6	3.15	26.9	2.E-06	1.23	1.19
6	4.5	16.9	7.4	9.8	3.04	26.1	5.E-06	1.32	1.21
7	4.9	19.1	8.6	10.0	2.69	25.3	2.E-05	1.41	1.23
8	5.4	21.5	9.8	10.2	2.56	24.7	4.E-05	1.50	1.23
9	5.9	23.9	11.0	10.4	2.86	24.2	8.E-05	1.57	1.21
10	6.3	26.0	12.2	10.6	3.43	23.8	1.E-04	1.62	1.19
15	7.5	34.1	17.9	11.3	6.70	21.7	5.E-04	1.84	1.17
20	8.3	41.3	23.5	11.9	8.93	19.8	9.E-04	2.02	1.17
30	9.7	56.2	34.8	13.0	9.09	16.9	3.E-03	2.38	1.19
40	11.5	75.4	46.4	14.0	5.13	15.0	1.E-02	2.81	1.24
50	14.4	101	58.5	14.8	4.81	14.0	4.E-02	3.26	1.25
60	16.6	124	70.5	15.4	6.62	13.2	1.E-01	3.60	1.24
70	18.4	145	82.3	16.0	8.25	12.4	1.E-01	3.91	1.24
80	19.9	167	94.1	16.5	9.51	11.7	2.E-01	4.20	1.24
90	21.3	189	106.0	17.0	10.40	11.1	2.E-01	4.48	1.25
100	22.6	211	118.0	17.4	10.90	10.5	3.E-01	4.76	1.26
110	23.9	235	130.0	17.9	11.10	10.0	3.E-01	5.03	1.27



(u_c-u^o)* (kJ/kg)
1E3
2E3
3E3
4E3
5E3
6E3
7E3
8E3
9E3
1E4
1.5E4
2E4
3E4
4E4
5E4
6E4
7E4
9E4
1.1E5
v_e* (km/s)
P_e = 2 bar
P_e = 1 bar
P_e = 5 bar
P_e = 0.1 bar
P_e = 10 bar
P_e =60 bar
throat
area ratio
2
4
8
16
32
64
128
256
512
1024
1E4
1E5
1E6
Equilibrium expansion
ρ_c = 1.18 kg/m³
normalized coupling coefficient, C*=C/beta, Ns/MJ
alpha
0.0
0.2
0.4
0.6
0.8
1.0
0
100
200
300
400
500



1E3
2E3
3E3
4E3
5E3
6E3
7E3
8E3
9E3
1E4
1.5E4
2E4
3E4
4E4
5E4
6E4
7E4
9E4
1.1E5
v_e* (km/s)
P_e = 0.1 bar
P_e = 1 bar
P_e = 10 bar
throat
area ratio
2
4
8
1024
Frozen expansion
ρ_c = 1.18 kg/m³
(u_c-u^o)* (kJ/kg)
normalized coupling coefficient, C*=C/beta, Ns/MJ
alpha
0.0
0.2
0.4
0.6
0.8
1.0
0
100
200
300
400
500



Conclusions

Coupling coefficients for Delrin are 2 to 3 times larger than for air in the MLL model 200-3/4.

Coupling coefficients are sensitive to beam quality.

Energy conversion efficiencies ($\alpha\beta$) are ~ 30% and increase to a plateau above E_L ~ 300 J/pulse.

Exit velocities of ~ 2000 m/s with Delrin (based on measured mass) and ~ 3000 m/s with air (based on estimated mass).

Based on the minimum entropy gain principle for blowdown expansion from initial equilibrium plasma states to 1 bar exit pressure, the upper limits to energy conversion efficiency (α) in expansion of heated STP air are ~ 0.26 (equilibrium) and ~ 0.23 (frozen). With air at its Mach 5 stagnation density, these values increase to ~ 0.45. Efficiencies are almost independent of the initial plasma temperature. Expansion ratios of 4 to 8 for STP air and 16 to 32 for Mach 5 air are required for P_e = 1 bar.